Light Quark Yukawa's

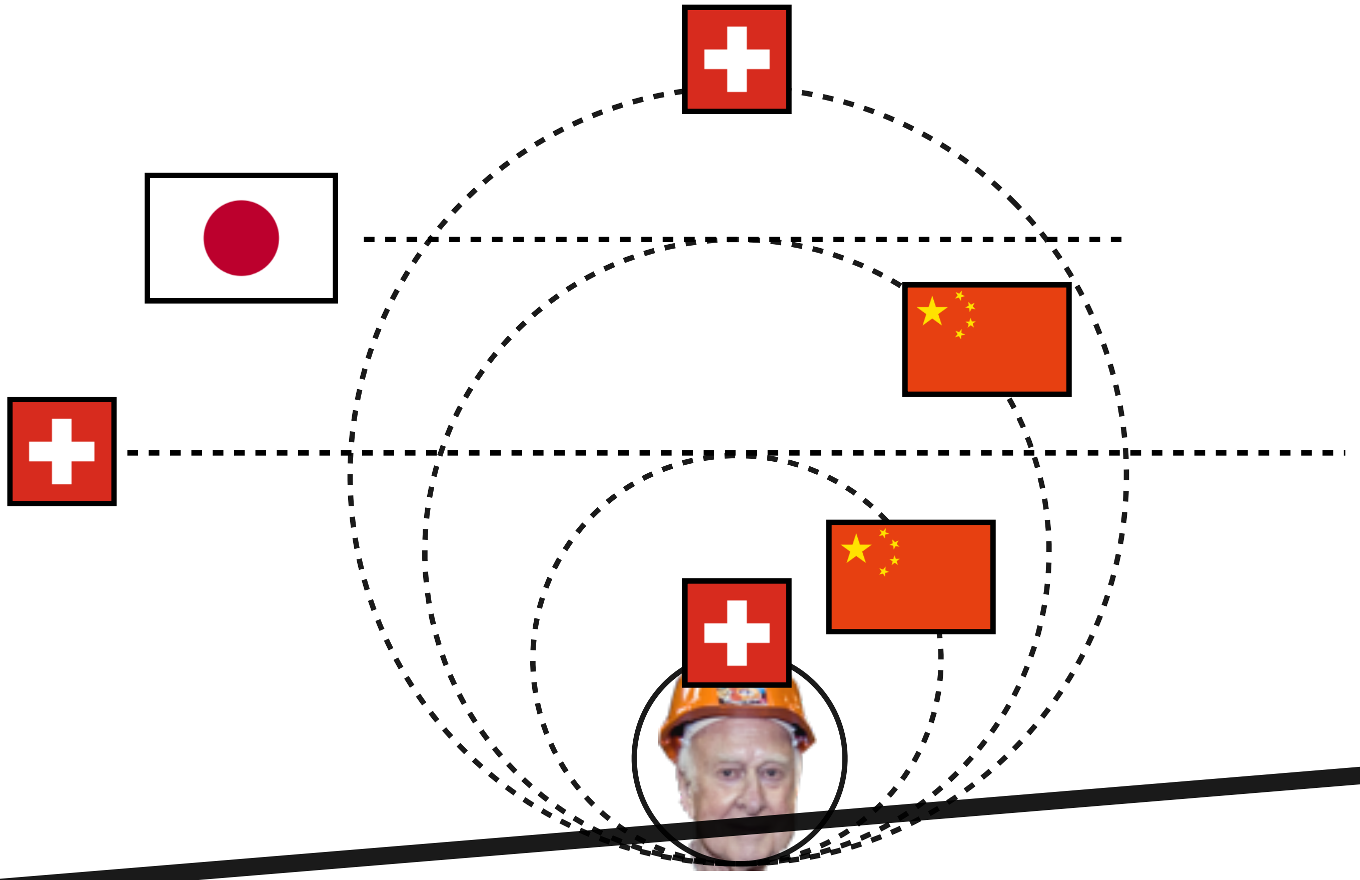
Snowmass Energy Frontier Workshop Restart

September 1, 2021

Christophe Grojean

with the (great) help of

Lina Alasfar, Ramona Gröber, Ayan Paul and Zhuoni Qian (and the Higgs@FC ECFA team)



Why looking at light Yukawa's?

The knowledge of the values of the **Higgs couplings** is essential to understand the deep structure of matter/Universe

$m_W, m_Z \leftrightarrow$ Higgs couplings ✓

$\uparrow$

lifetime of stars

(why $t_{Sun} \sim t_{life\ evolution}$?)

$m_e, m_u, m_d \leftrightarrow$ Higgs couplings ?

size of atoms

nuclei stability

Obvious that Higgs mechanism is at the origin of the light masses?

Well, it was also obvious in the 50's that weak interactions are parity invariant…

Which Scale?

Flavour agnostic

$$\frac{c_{ij}}{\Lambda^2}|H|^2\bar{\psi}H\psi \Rightarrow \kappa_q \equiv \frac{y_q}{y_q^{\rm SM}} = 1 + c_q\frac{v^3}{m_q\Lambda^2} \Rightarrow \begin{cases} \kappa_u = 1000 \to \Lambda = 3\,\text{TeV} \\ \kappa_d = 100 \to \Lambda = 5\,\text{TeV} \\ \kappa_s = 10 \to \Lambda = 4\,\text{TeV} \\ \Delta\kappa_c = 1 \to \Lambda = 3.5\,\text{GeV} \end{cases}$$

but need to pay attention to FCNC (generically Λ>1000 TeV)

large deviations in light Yukawa likely excluded by flavour data → don't waste time probing with Higgs

Minimal Flavour Violation

$$\frac{c\,Y_{ij}^{SM}}{\Lambda^2}|H|^2\bar{\psi}_iH\psi_j \Rightarrow \kappa_q = 1 + c_q\frac{v^2}{\Lambda^2} \Rightarrow \begin{cases} \kappa_q = 100 \to \Lambda = 20\,\text{GeV} \\ \kappa_q = 0.1 \to \Lambda = 800\,\text{GeV} \end{cases}$$

usually fine with respect to flavour data (Λ>O(few) TeV)

fine with flavour but signal very difficult to see in Higgs physics
(except maybe for charm quark)

Challenge
build flavour models that avoid large FCNC and still generate large deviations in light Yukawa's

interesting model building: Spontaneous Flavour Violation or Aligned Flavour Violation

Delaunay, Grojean, Perez '13 — Egana-Ugrinovic, Homiller, Meade, '18 — Bar-Shalom, Soni, '18

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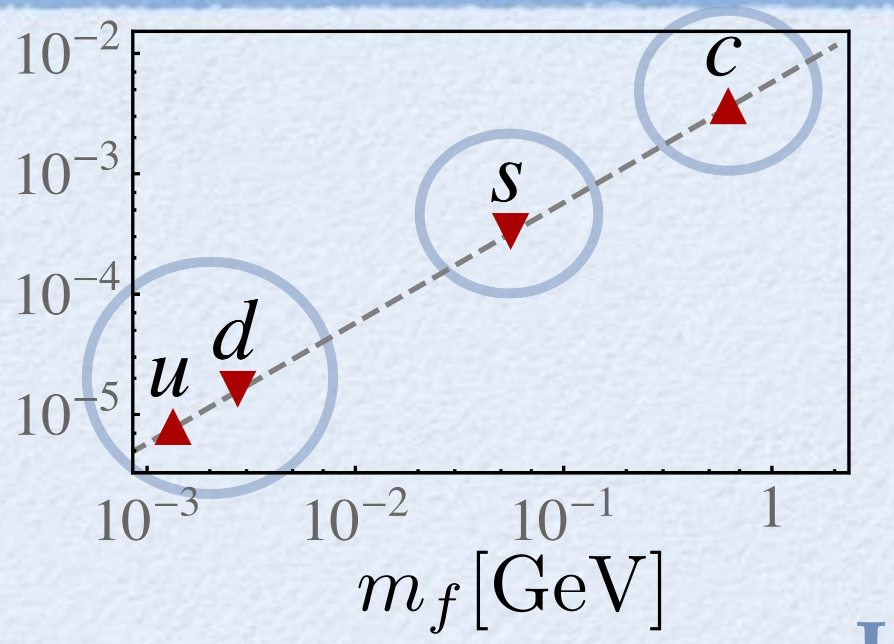
Delaunay, Grojean, Perez '13 Egana-Ugrinovic, Homiller, Meade, '18 Bar-Shalom, Soni, '18

PROBING LIGHT QUARK YUKAWAS

Yotam Soreq, Exotic Higgs decays workshop, SLAC '16

$$y_f^{\rm SM} = \frac{m_f}{v}$$



inclusive rates

Delaunay, Golling, Perez, YS, 1310.7029
Perez, YS, Stamou, Tobioka, 1505.06689, 1503.00290
Brivio, Goertz, Isidori, 1507.02916
ATLAS, 1407.0608
ATLAS, 1501.01325
ATL-PHYS-PUB-2015-001

exclusive rates ($h \to \gamma V$)

Bodwin, Petriello, Stoynev, Velasco, 1306.5770
Kagan, Perez, Petriello, YS, Stoynev, Zupan, 1406.1722
Bodwin, Chung, Ee, Lee, Petriello 1407.6695
Perez, YS, Stamou, Tobioka 1503.00290
Koing, Neubert, 1505.03870
ATLAS, 1501.03276, 1607.03400
CMS, 1507.03031

Higgs kinematics

Bishara, Haisch, Monni, Re 1606.09253
YS, Zhu, Zupan 1606.09621

Higgs production

Zhou, 1505.06369
Yu 1609.06592

Yukawa's from Global Fits

$$\mathcal{O}_6 = -\lambda |H|^6$$

$\mathcal{O}_H = \frac{1}{2}(\partial_\mu \vert H^2 \vert)^2$ $\mathcal{O}_{WW} = g^2 \vert H \vert^2 W^a_{\mu\nu} W^{a,\mu\nu}$ $\mathcal{O}_{BB} = g'^2 \vert H \vert^2 B_{\mu\nu} B^{\mu\nu}$ $\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$ $\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$	$\mathcal{O}_{GG} = g_s^2 \vert H \vert^2 G^A_{\mu\nu} G^{A,\mu\nu}$ $\mathcal{O}_{y_u} = y_u \vert H \vert^2 \bar{q}_L \tilde{H} u_R + \text{h.c.}$ $\mathcal{O}_{y_d} = y_d \vert H \vert^2 \bar{q}_L H d_R + \text{h.c.}$ $\mathcal{O}_{y_e} = y_e \vert H \vert^2 \bar{l}_L H e_R + \text{h.c.}$ $\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon_{abc} W^{a\,\nu}_\mu W^b_{\nu\rho} W^{c\,\rho\mu}$
$\mathcal{O}_W = \frac{ig}{2}(H^\dagger \sigma^a \overleftrightarrow{D}_\mu H) D^\nu W^a_{\mu\nu}$	$\mathcal{O}_B = \frac{ig'}{2}(H^\dagger \overleftrightarrow{D}_\mu H) \partial^\nu B_{\mu\nu}$
$\mathcal{O}_{WB} = gg' H^\dagger \sigma^a H W^a_{\mu\nu} B^{\mu\nu}$ $\mathcal{O}_T = \frac{1}{2}(H^\dagger \overleftrightarrow{D}_\mu H)^2$ $\mathcal{O}_{\ell\ell} = (\bar{\ell}_L \gamma^\mu \ell_L)(\bar{\ell}_L \gamma_\mu \ell_L)$	$\mathcal{O}_{H\ell} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{\ell}_L \gamma^\mu \ell_L$ $\mathcal{O}'_{H\ell} = iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H \bar{\ell}_L \sigma^a \gamma^\mu \ell_L$ $\mathcal{O}_{He} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{e}_R \gamma^\mu e_R$
$\mathcal{O}_{Hq} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{q}_L \gamma^\mu q_L$ $\mathcal{O}'_{Hq} = iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H \bar{q}_L \sigma^a \gamma^\mu q_L$	$\mathcal{O}_{Hu} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{u}_R \gamma^\mu u_R$ $\mathcal{O}_{Hd} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{d}_R \gamma^\mu d_R$

- SILH' basis (eliminate $\mathcal{O}_{WW}$, $\mathcal{O}_{WB}$, $\mathcal{O}_{H\ell}$ and $\mathcal{O}'_{H\ell}$)
- Modified-SILH' basis (eliminate $\mathcal{O}_W$, $\mathcal{O}_B$, $\mathcal{O}_{H\ell}$ and $\mathcal{O}'_{H\ell}$)
- Warsaw basis (eliminate $\mathcal{O}_W$, $\mathcal{O}_B$, $\mathcal{O}_{HW}$ and $\mathcal{O}_{HB}$)

- Flavour assumptions
  - flavour universality: 19
  - flavour diagonality: 31-33

c, b, t, μ, τ Yukawa only
U(2) symmetry
among 2 first quark generations

BR_{inv} and $BR_{untagged}$
to take into account
light quark generations

Yukawa's from Global Fits

kappa-3 scenario	HL-LHC	HL-LHC + LHeC	HL-LHC + HE-LHC (S2)	HL-LHC + HE-LHC (S2')
$1 \geq \kappa_W > (68\%)$	0.985	0.996	0.988	0.992
$1 \geq \kappa_Z > (68\%)$	0.987	0.993	0.989	0.993
κ_g (%)	$\pm 2.$	± 1.6	± 1.6	$\pm 1.$
κ_γ (%)	± 1.6	± 1.4	± 1.2	± 0.82
$\kappa_{Z\gamma}$ (%)	$\pm 10.$	$\pm 10. *$	± 5.5	± 3.7
κ_c (%)	–	± 3.7	–	–
κ_t (%)	± 3.2	$\pm 3.2 *$	± 2.6	± 1.6
κ_b (%)	± 2.5	± 1.2	$\pm 2.$	± 1.4
κ_μ (%)	± 4.4	$\pm 4.4 *$	± 2.2	± 1.5
κ_τ (%)	± 1.6	± 1.4	± 1.2	± 0.77
BR_{inv} (<%, 95% CL)	1.9	1.1	1.8 *	1.5 *
BR_{unt} (<%, 95% CL)	inferred using constraint $\lvert\kappa_V\rvert \leq 1$			
	4.	1.3	3.3	2.4

Table 13. Upper bounds on the κ_i for u, d, s and c (at hadron colliders) at 95% CL, obtained from the upper bounds on BR_{unt} in the kappa-3 scenario.

	HL-LHC	+LHeC	+HE-LHC	+ILC$_{500}$	+CLIC$_{3000}$	+CEPC	+FCC-ee$_{240}$	+FCC-ee/eh/hh
κ_u	560.	320.	430.	330.	430.	290.	310.	280.
κ_d	260.	150.	200.	160.	200.	140.	140.	130.
κ_s	13.	7.3	9.9	7.5	9.9	6.7	7.	6.4
κ_c	1.2		0.87	measured directly				

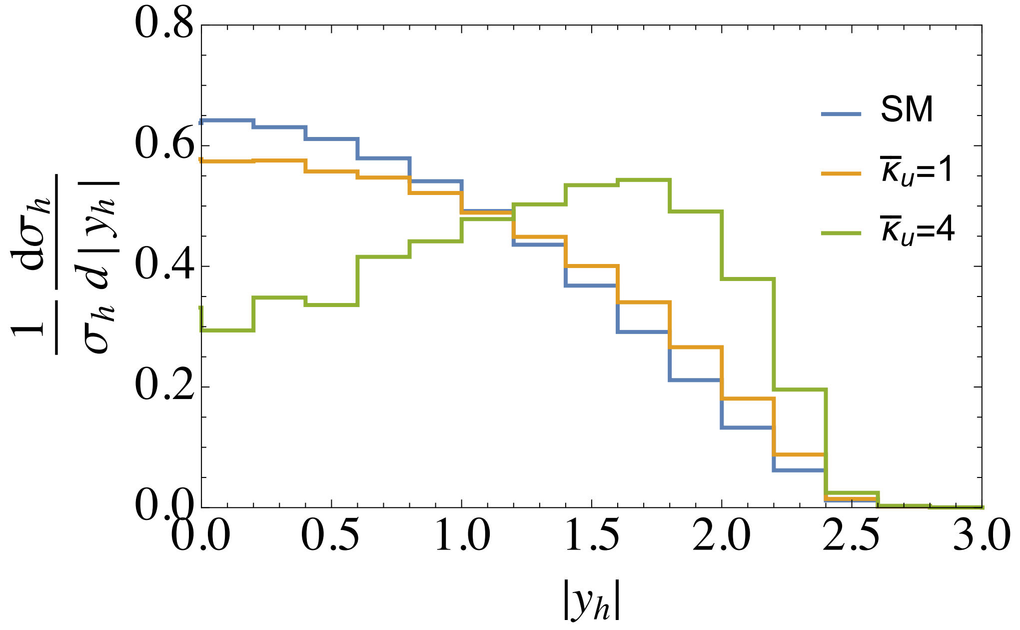
Higgs Kinematics (valence quarks)

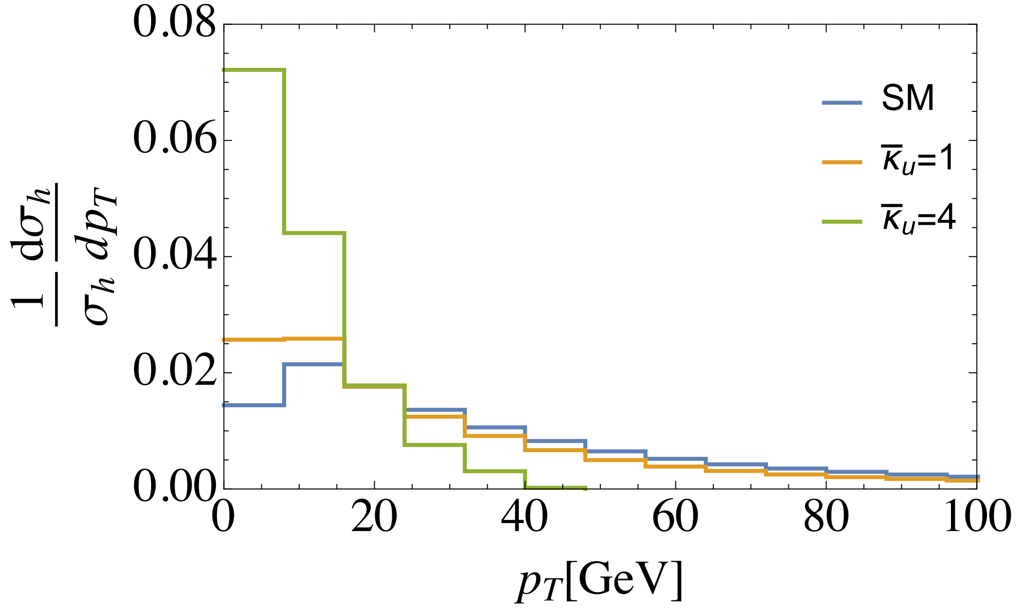
valance quarks carry larger fraction of the proton momentum → more forward yh spectrum

gluons has stronger radiation than quarks → softer pT spectrum in presence of quark fusion

Soreq, Zhu, Zupan, '16

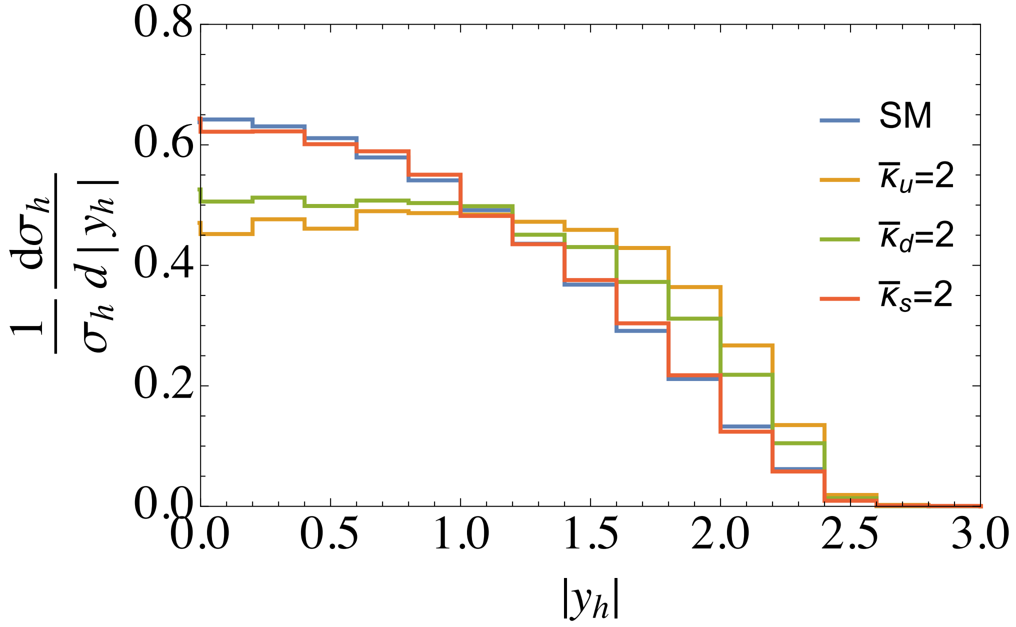
$$\bar{\kappa}_q = \frac{y_q^{\rm exp}}{y_b^{\rm SM}}$$

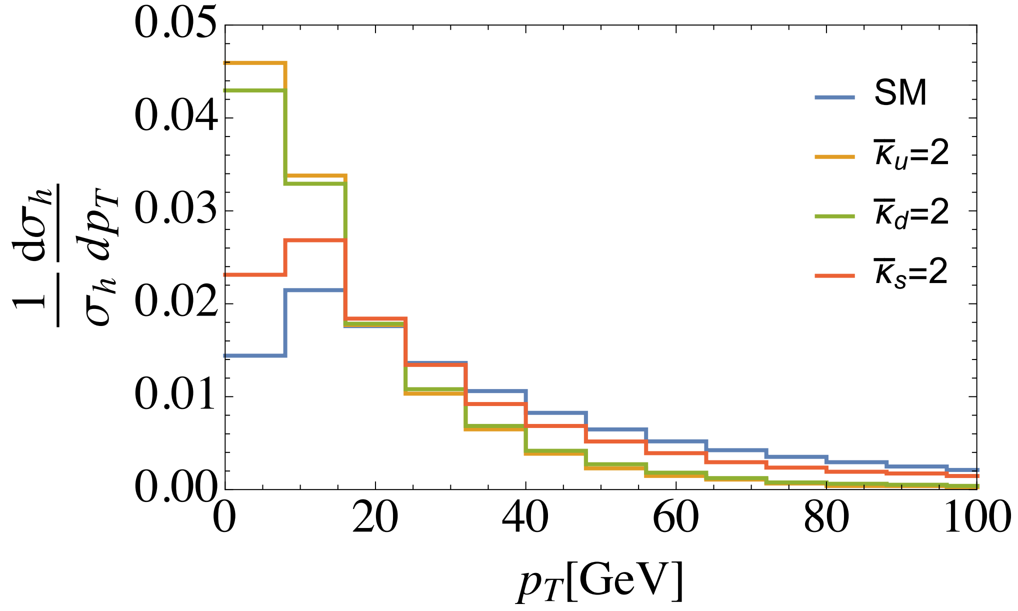




$\kappa_u \sim 2000$

$\kappa_u \sim 8000$





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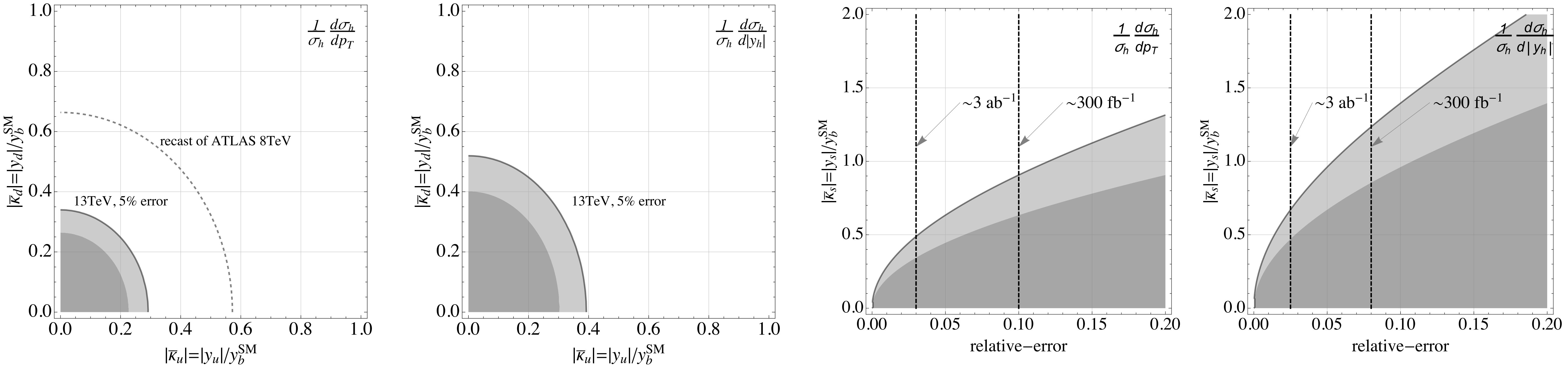


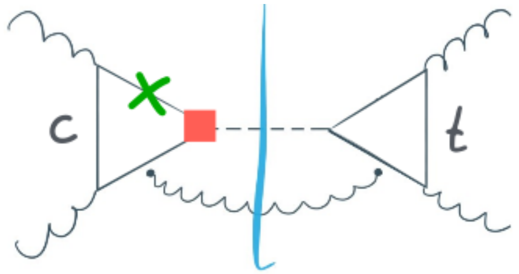
$$\bar{\kappa}_q = \frac{y_q^{\rm exp}}{y_b^{\rm SM}}$$

Higgs Kinematics (heavier quarks)

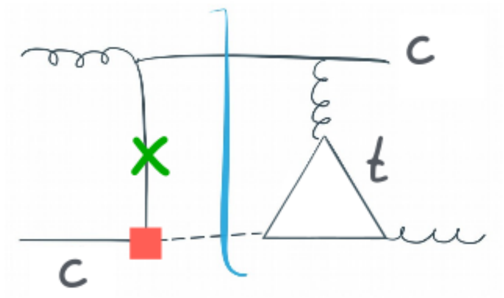
quark contribution to ggF production is chirality suppressed but charm is special bc of non-Sudakov double logs

Color coding courtesy of Uli Haisch

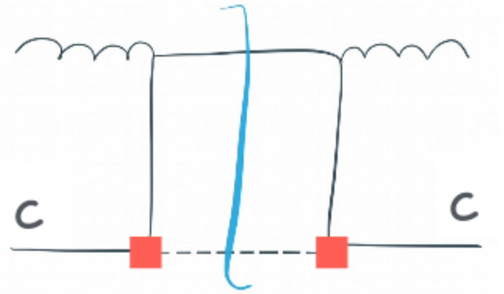
Bishara, Haisch, Monni, Re '16



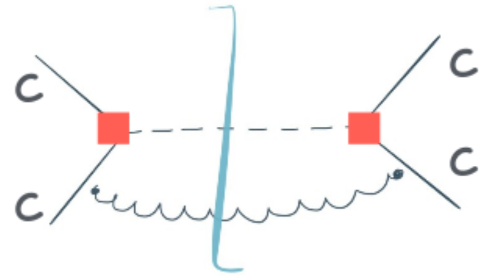
$$\sim \alpha_s^3 y_c m_c \ln^2\left(\frac{p_T^2}{m_c^2}\right)$$



$$\sim \alpha_s \alpha_s^2 y_c m_c \quad (= 0 \text{ in 4, 5 flavour scheme})$$



$$\sim \alpha_s \alpha_s y_c^2$$



$$\sim \alpha_s^2 \alpha_s y_c^2$$

chirality flip

extra powers of α_s from charm PDF

[Sullivan, Nadolsky: hep-ph/0111358]

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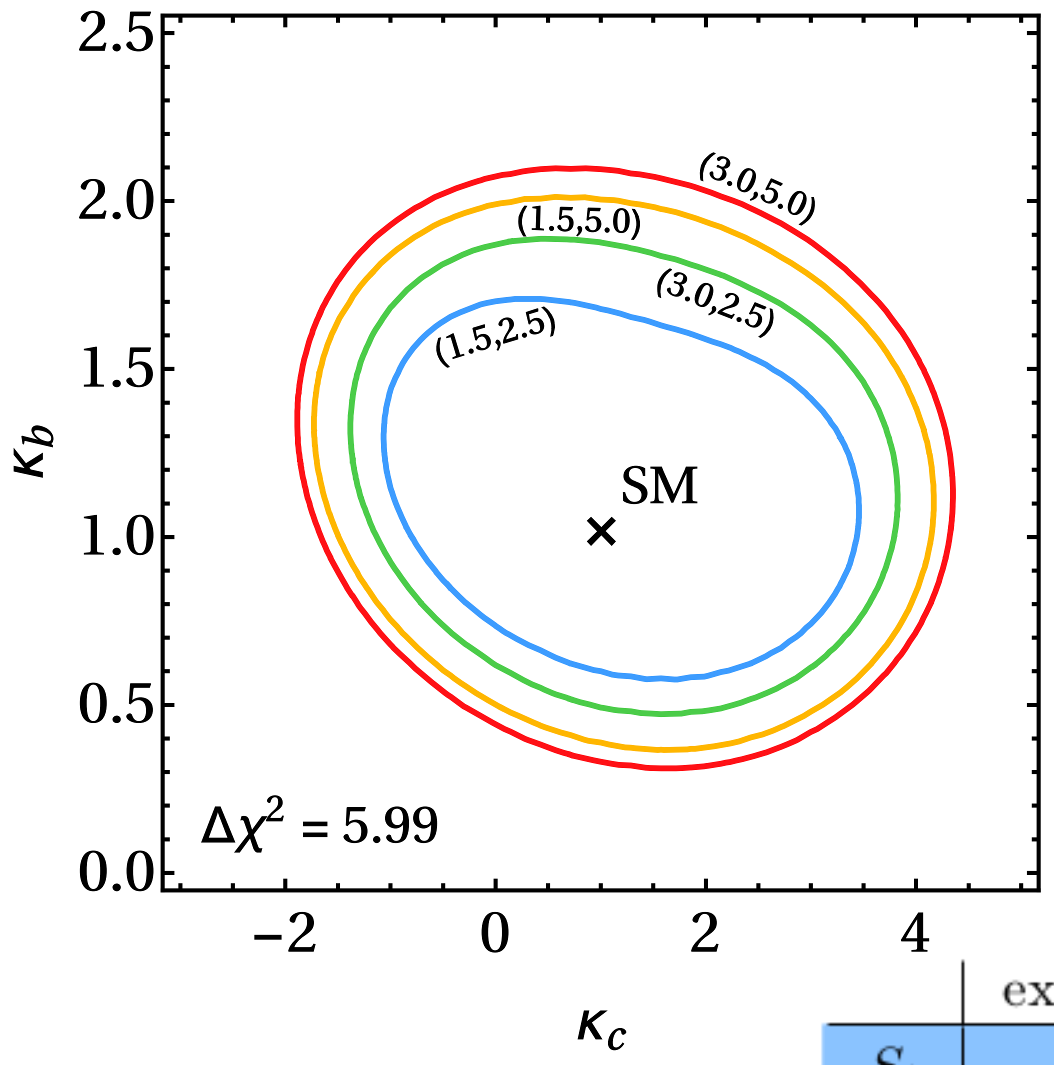
Bishara, Haisch, Monni, Re '16



95% C.I. after profiling over κ_b

LHC Run I: $[-16, 18]$

LHC Run II: $[-1.4, 3.8]$

HL-LHC: $[-0.6, 3.0]$

CMS with 35.9 fb^{-1} (13 TeV)

$-8.7 < \kappa_c < 10.6$

PAS HIG-17-028

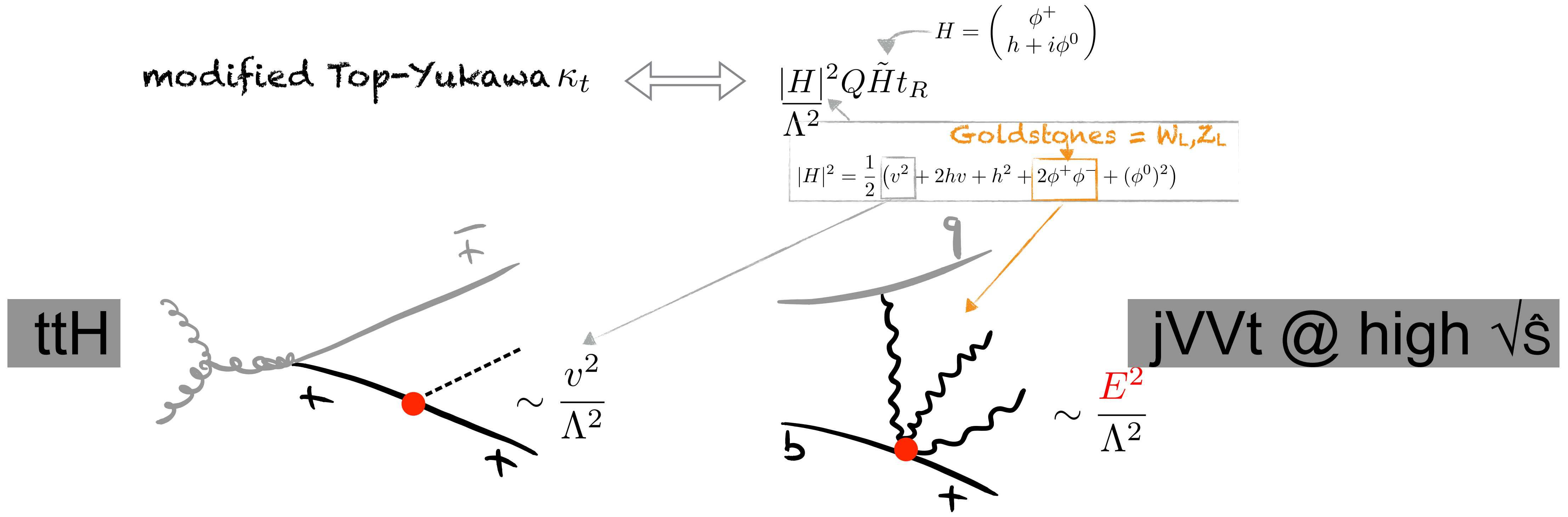
	experimental [%]	theoretical [%]	$\kappa_c \in$
S_1	1.5	2.5	[-0.6, 3.0]
S_2	3.0	2.5	[-0.9, 3.3]
S_3	1.5	5.0	[-1.2, 3.6]
S_4	3.0	5.0	[-1.3, 3.7]

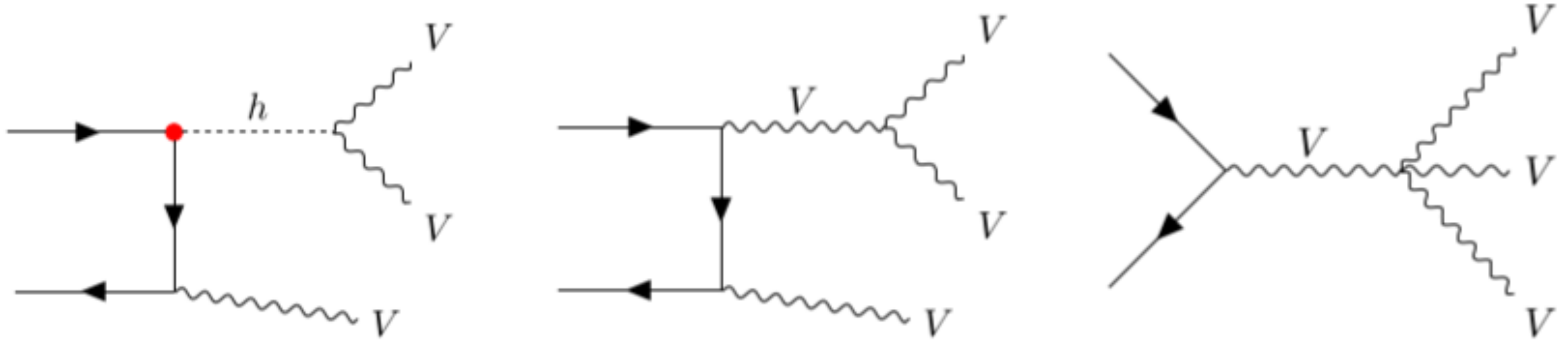
Yukawa’s from Processes without Higgs

“Higgs without Higgs” philosophy

Henning, Lombardo, Riembau, Riva ‘18

Riva @ Higgs 2020





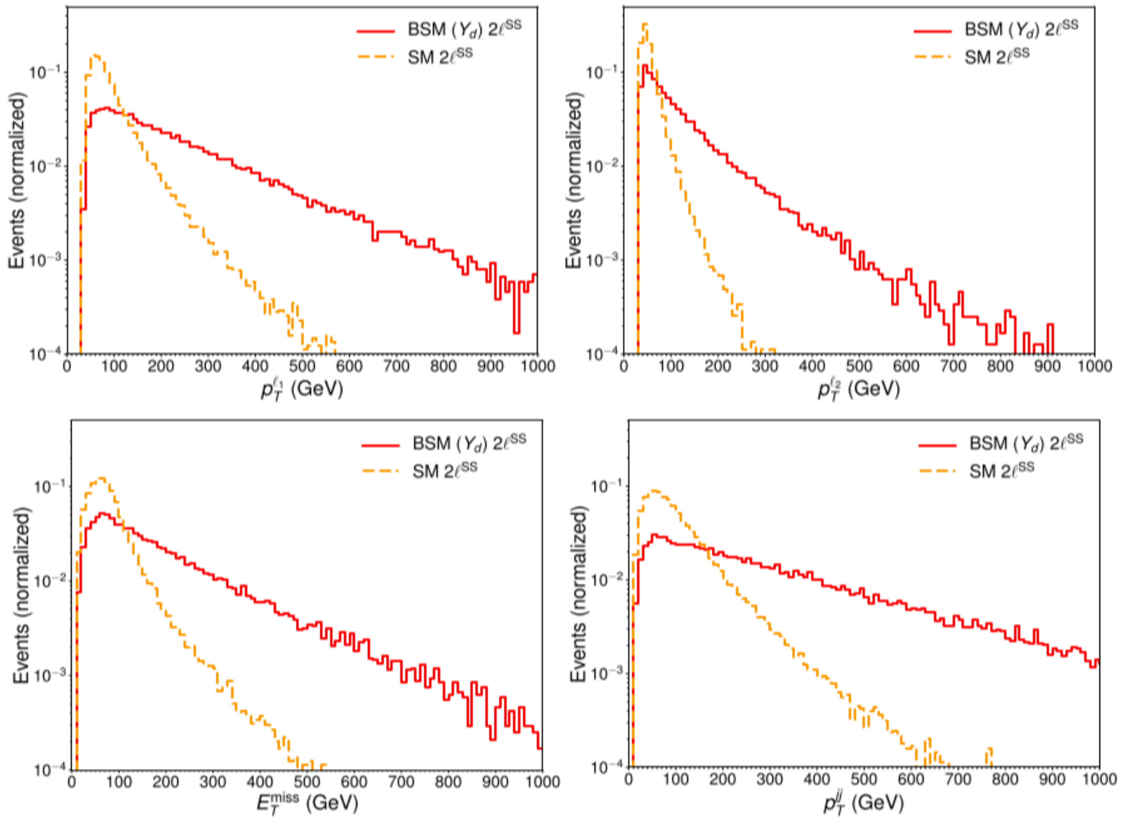
modified Yukawa spoils cancelation of energy growing terms in amplitudes

→ large effects in the tails

Yukawa's from Processes without Higgs

WWW: same-sign di-lepton final state

- **Process:** $pp \to W^\pm W^\pm W^\mp \to \ell^\pm \ell^\pm \nu\nu jj$ **cross-section:** $\sigma(Y_d) = 7.5\,\text{fb} + Y_d^2 \times 210\,\text{fb}$
- Improve **HL-LHC** sensitivity by **more stringent** cuts



$$p_T^{\ell_{1,2}} > 60\,\text{GeV}\,, \quad E_T^{\text{miss}} > 120\,\text{GeV}\,, \quad p_T^{jj} > 120\,\text{GeV}\,, \quad |\Delta\eta(\ell_1,\ell_2)| < 2$$

$$\epsilon_S = 0.61 \text{ (HL-LHC)}$$
$$\epsilon_B = 0.015 \text{ (HL-LHC)}$$

(With **pTll differential distribution** shape)

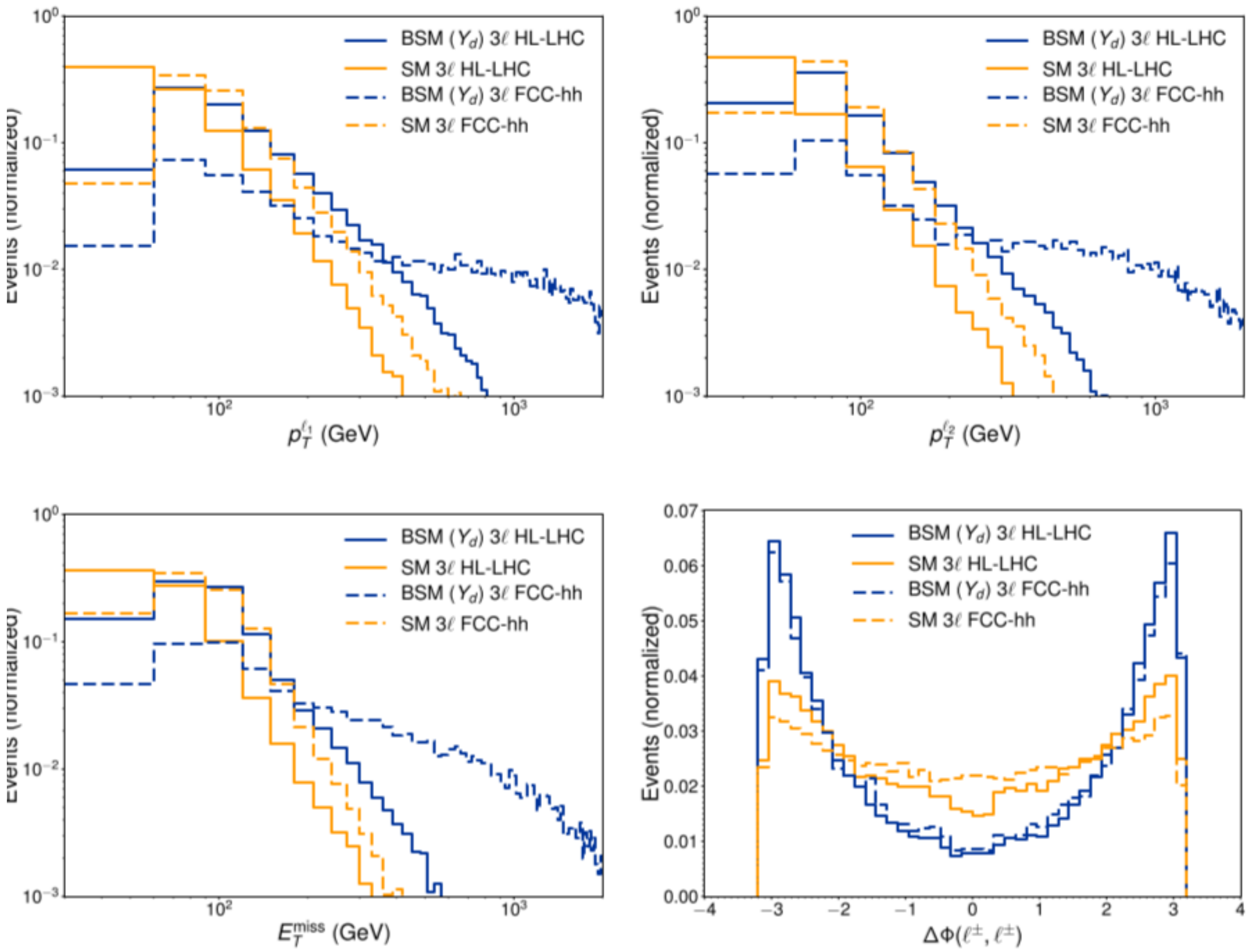
$$\delta y_d \lesssim 430 \text{ (HL-LHC)}$$
$$\delta y_u \lesssim 850 \text{ (HL-LHC)}$$
$$\delta y_s \lesssim 150 \text{ (HL-LHC)}$$

Falkowski, Ganguly, Gras, No, Tobioka, Vignaroli, You '20

Yukawa's from Processes without Higgs

WWW: tri-lepton final state

- **Process** $pp \to W^\pm W^\pm W^\mp \to \ell^\pm \ell^\pm \ell^\mp \nu\nu\nu$



HL-LHC:

$$p_T^{\ell_1} > 70\,\text{GeV}\,,\; p_T^{\ell_2} > 50\,\text{GeV}\,,\; p_T^{\ell_3} > 30\,\text{GeV}\,,\; E_T^{\text{miss}} > 80\,\text{GeV}\,,\; |\Delta\Phi(\ell^\pm,\ell^\pm)| > 2$$

FCC-hh:

$$p_T^{\ell_1} > 150\,\text{GeV}\,,\; p_T^{\ell_2} > 80\,\text{GeV}\,,\; p_T^{\ell_3} > 50\,\text{GeV}\,,\; E_T^{\text{miss}} > 120\,\text{GeV}\,,\; |\Delta\Phi(\ell^\pm,\ell^\pm)| > 1.5$$

$$\begin{aligned} \epsilon_S &= 0.62\ (\text{HL-LHC}) \quad , \quad \epsilon_S = 0.50\ (\text{FCC-hh})\,, \\ \epsilon_B &= 0.037\ (\text{HL-LHC}) \quad , \quad \epsilon_B = 0.014\ (\text{FCC-hh})\,. \end{aligned}$$

(Reducible background **negligible**)

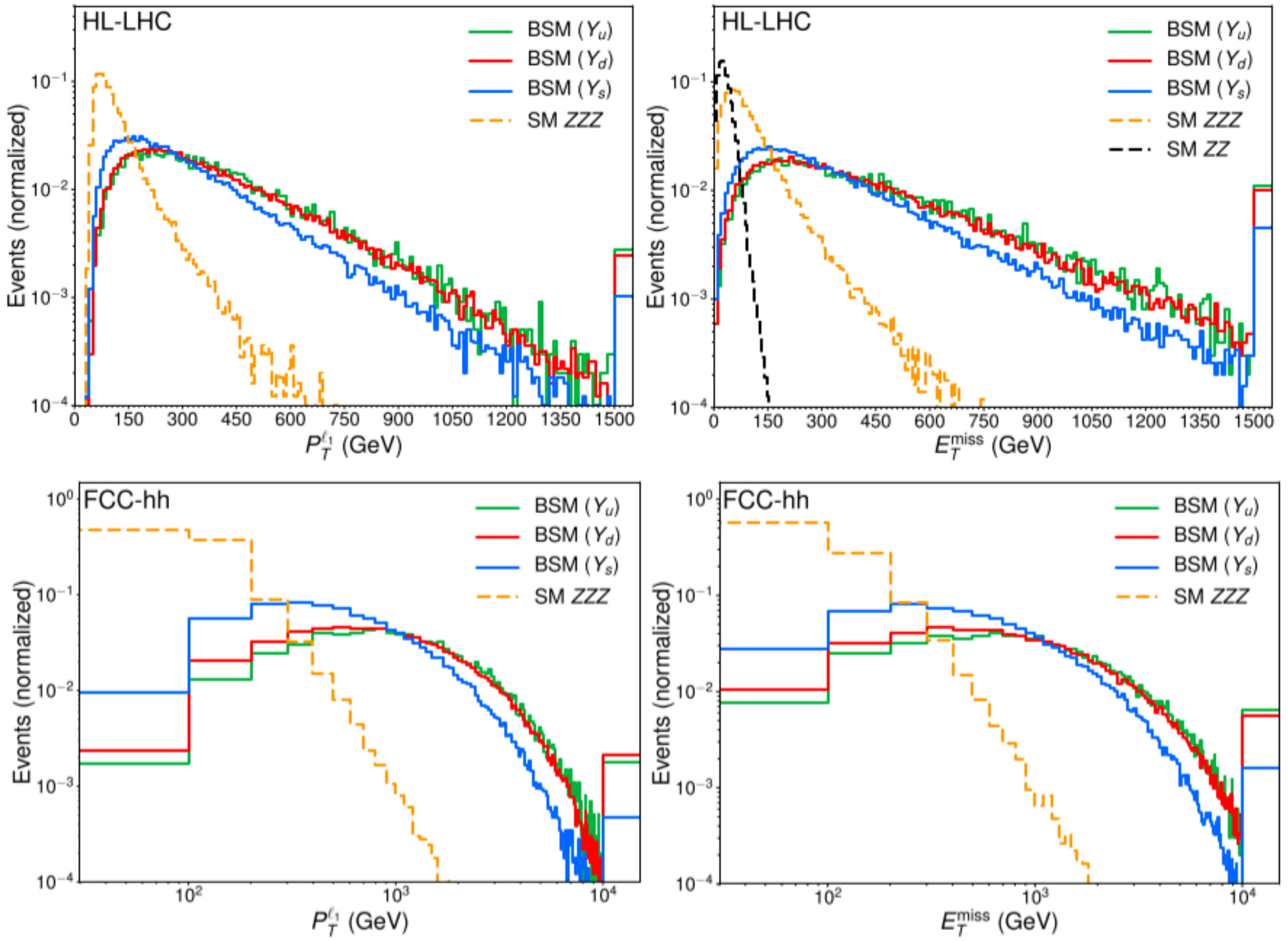
$$\begin{aligned} \delta y_d &\lesssim 900\ (\text{HL-LHC}) \quad , \quad \lesssim 120\ (\text{FCC-hh})\,, \\ \delta y_u &\lesssim 1900\ (\text{HL-LHC}) \quad , \quad \lesssim 240\ (\text{FCC-hh})\,, \\ \delta y_s &\lesssim 230\ (\text{HL-LHC}) \quad , \quad \lesssim 40\ (\text{FCC-hh})\,. \end{aligned}$$

Falkowski, Ganguly, Gras, No, Tobioka, Vignaroli, You '20

Yukawa's from Processes without Higgs

ZZZ: four-lepton final state

- **Process** $pp \to ZZZ \to 4\ell + 2\nu$ **cross-section:** $\sigma(Y_d) = 0.013\,\text{fb} + Y_d^2 \times 1.8\,\text{fb}\,,$



$p_T^{\ell_{1,2}} > 25$ GeV , $p_T^{\ell_{3,4}} > 10$ GeV , $|\eta_\ell| < 2.5$, $\Delta R_{\ell\ell} > 0.1$, $|m_Z - m_{\ell\ell}| < 10$ GeV .

HL-LHC:

$$E_T^{\text{miss}} > 200\ \text{GeV}.$$

FCC-hh:

$$\Delta R_{\ell\ell} > 0.01 \qquad E_T^{\text{miss}} > 500\ \text{GeV}$$

(Using **ETmiss differential distribution** shape)

$$\delta y_d \lesssim 1500 \quad (\text{HL-LHC}) \quad , \quad \lesssim 65 \quad (\text{FCC-hh})\,,$$
$$\delta y_u \lesssim 2300 \quad (\text{HL-LHC}) \quad , \quad \lesssim 100 \quad (\text{FCC-hh})\,,$$
$$\delta y_s \lesssim 300 \quad (\text{HL-LHC}) \quad , \quad \lesssim 12 \quad (\text{FCC-hh})\,.$$

Falkowski, Ganguly, Gras, No, Tobioka, Vignaroli, You '20

Yukawa's from Processes without Higgs

- **2σ sensitivity** estimates $\mathcal{L} \supset -\frac{h}{v} \sum_{q=u,d,s} m_q(1+\delta y_q)\bar{q}q$

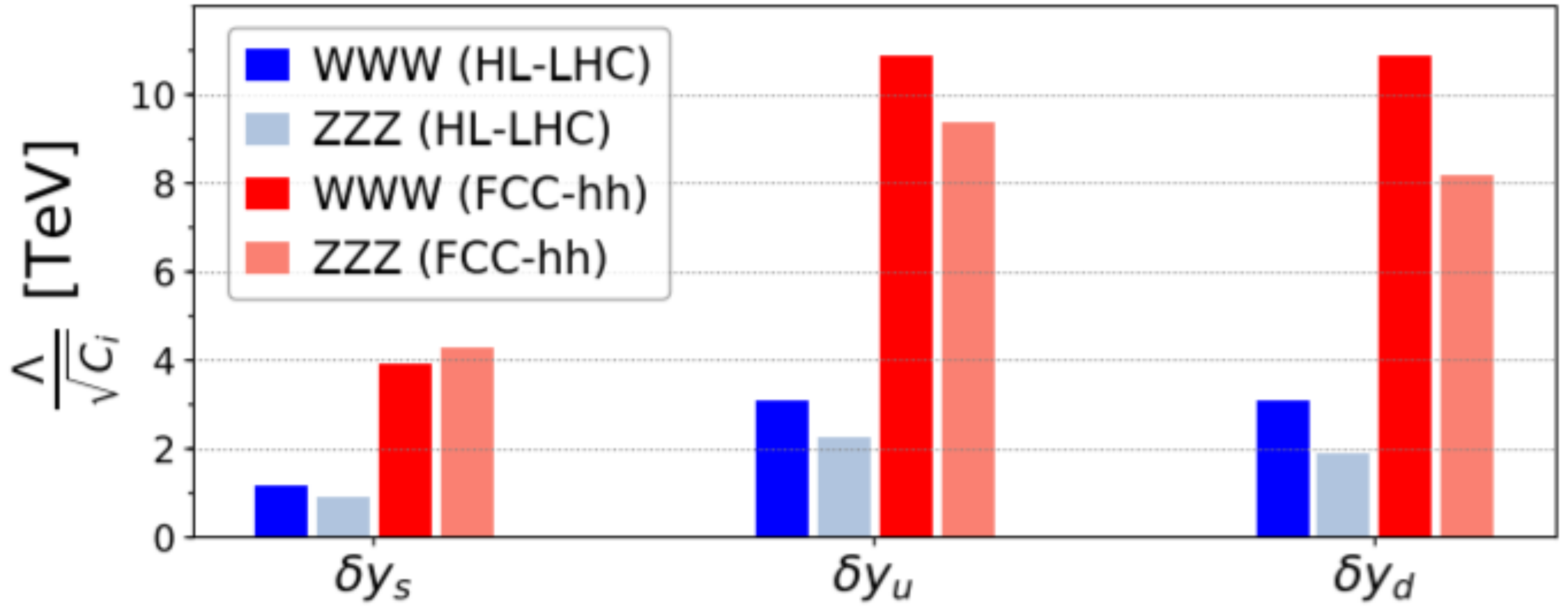
	WWW			ZZZ		
	$\ell^\pm\ell^\pm + 2\nu + 2j$	$\ell^\pm\ell^\pm\ell^\mp + 3\nu$	Comb.	$4\ell + 2\nu$	$4\ell + 2j$	Comb.
δy_d	430 (36)	840 (54)	420 (34)	1500 (65)	1300 (93)	1100 (60)
δy_u	850 (71)	1700 (110)	830 (68)	2300 (100)	1800 (140)	1600 (92)
δy_s	150 (13)	230 (33)	140 (13)	300 (12)	290 (16)	250 (11)

HL-LHC sensitivity

(FCC-hh sensitivity)

T. You @ MBI'21

- **Dimension-6 operator** scale $\mathcal{L}_{\rm SMEFT} \supset \frac{Y_u|H|^2}{v^2}\bar{u}_R Q_{1,L} H + \frac{Y_d|H|^2}{v^2}\bar{d}_R H^\dagger Q_{1,L} + \frac{Y_s|H|^2}{v^2}\bar{s}_R H^\dagger Q_{2,L} + \text{h.c.}$



$$\delta y_q = -\frac{Y_q}{y_q^{\rm SM}}$$

$$Y_i = C_i\, v^2/\Lambda^2$$

Yukawa's from Higgs² production

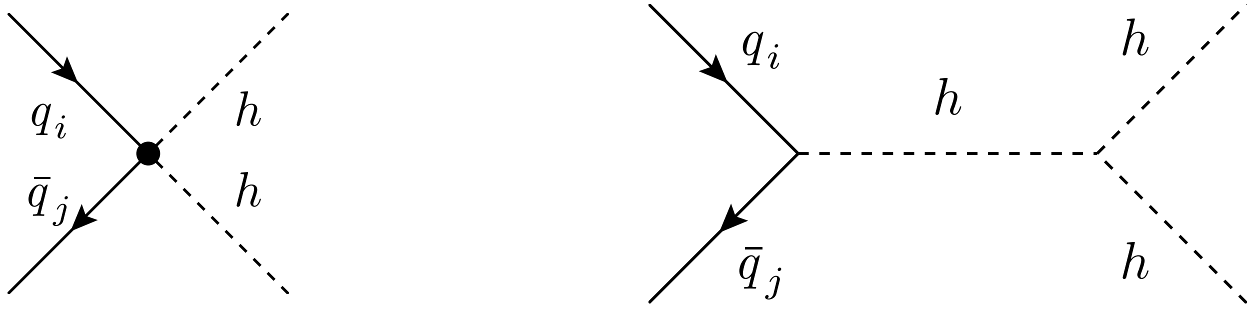
large Yukawa's for light quarks → new (dominant) contribution to HH production

Alasfar, Corral Lopez, Gröber, '19

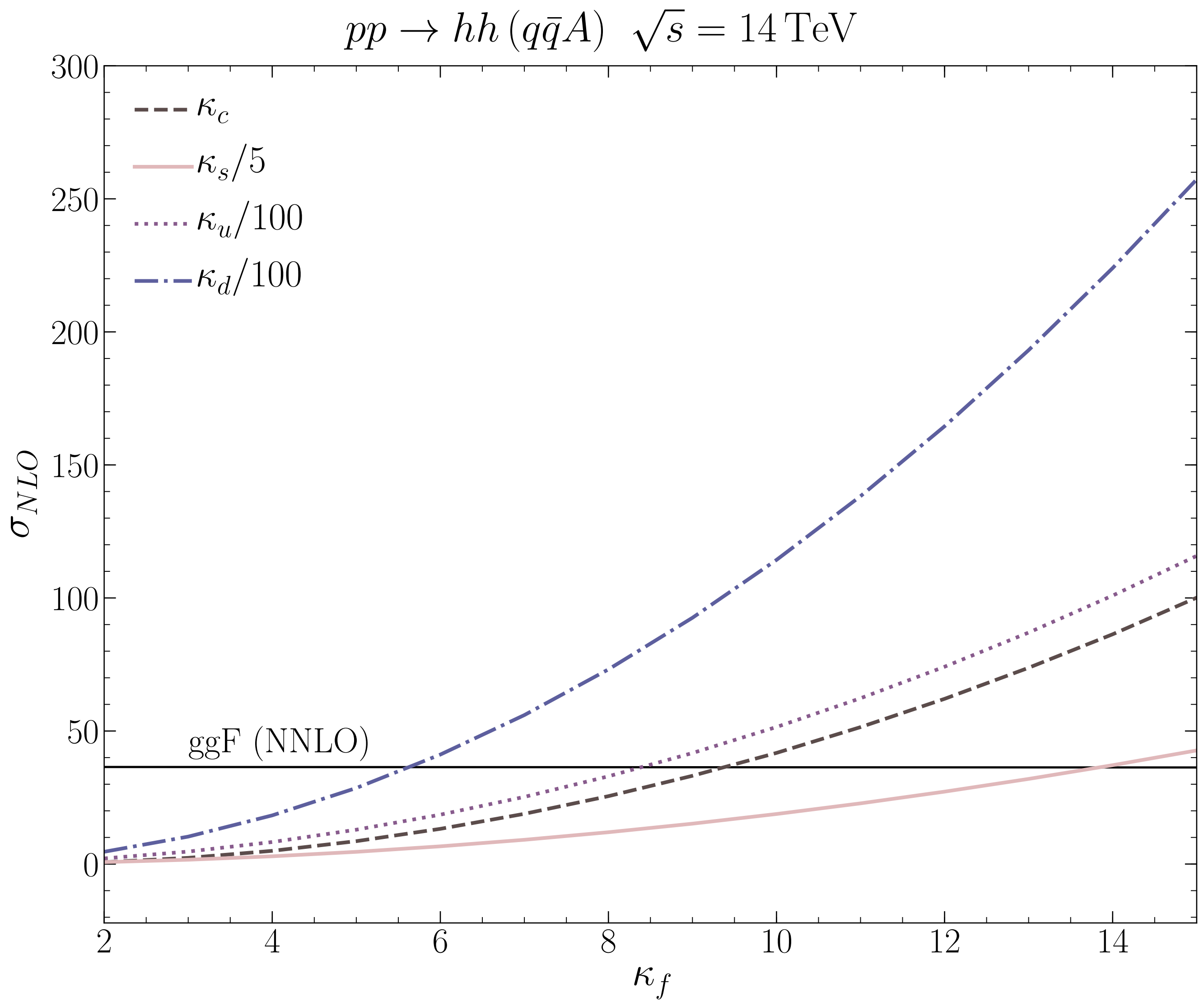
see also, Egana-Ugrinovic, Homiller, Meade, '21

SMEFT structure

(not present in HEFT)



$$g_{hhq_i\bar{q}_i} = -\frac{3}{2}\frac{1-\kappa_q}{v} g^{\text{SM}}_{hq_i\bar{q}_i},$$



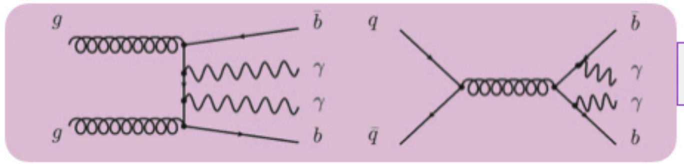
HH more sensitive than H because of SM negative interference in HH

but h³ coupling is also largely unknown

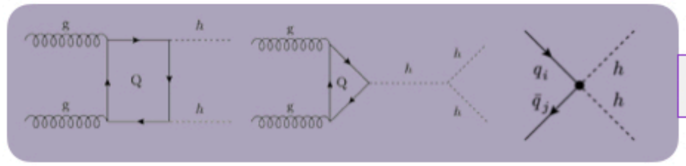
Yukawa's from Higgs² production

Alasfar, Gröber, Grojean, Paul, Qian, in progress

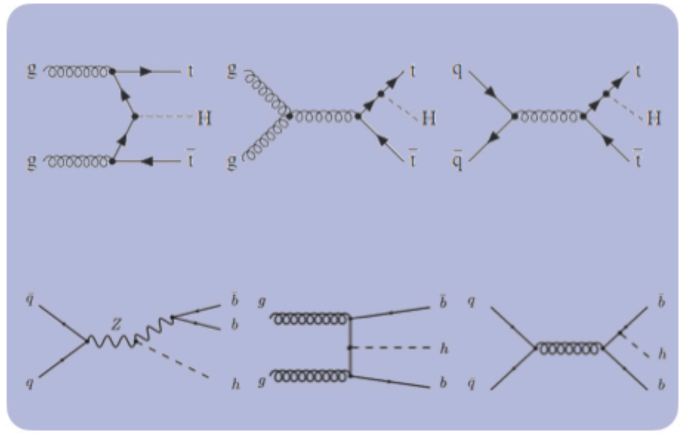
Interpretable Variables



QCD-QED Backgrounds



hh signal



$b\bar{b}h + t\bar{t}h$ backgrounds

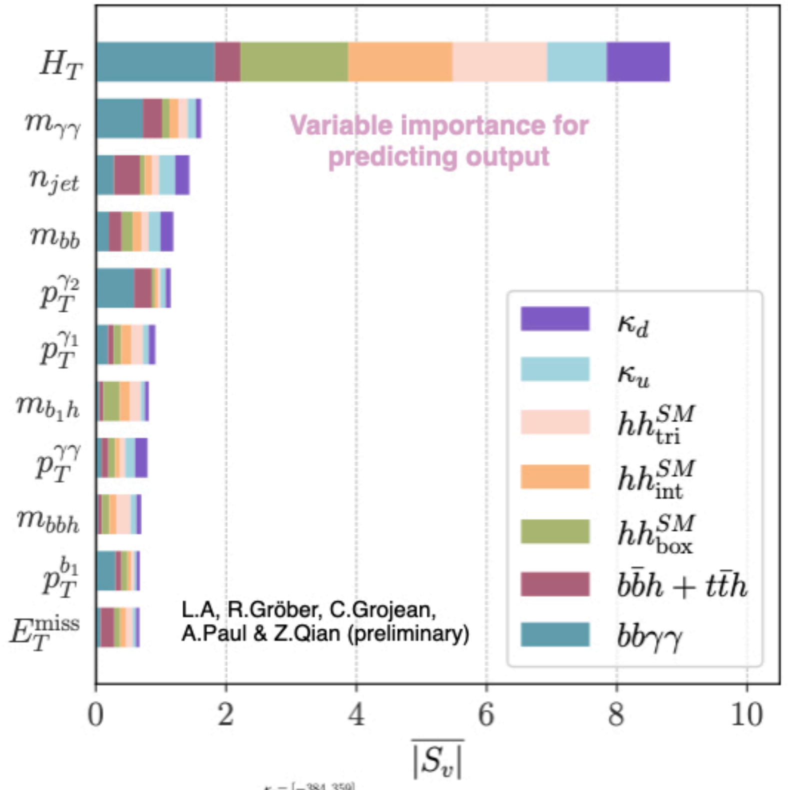
Generate Monte Carlo events, with Parton shower and fast detector effects

Construct high-level kinematic observables (features), with basic cuts

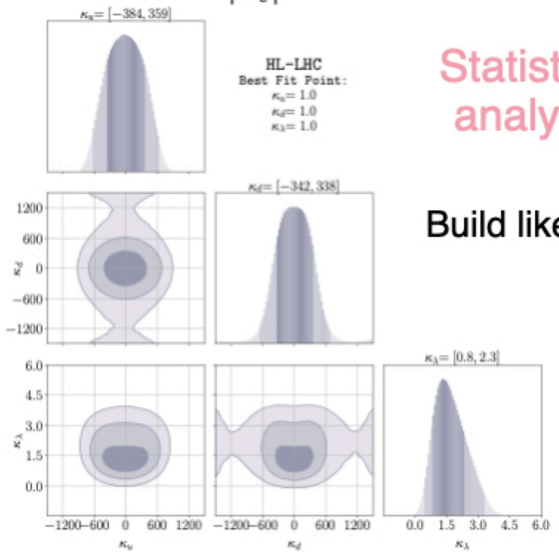
Shapley values + Physics Insights

Boosted Decision Trees + Signal Classification

Interpretable models



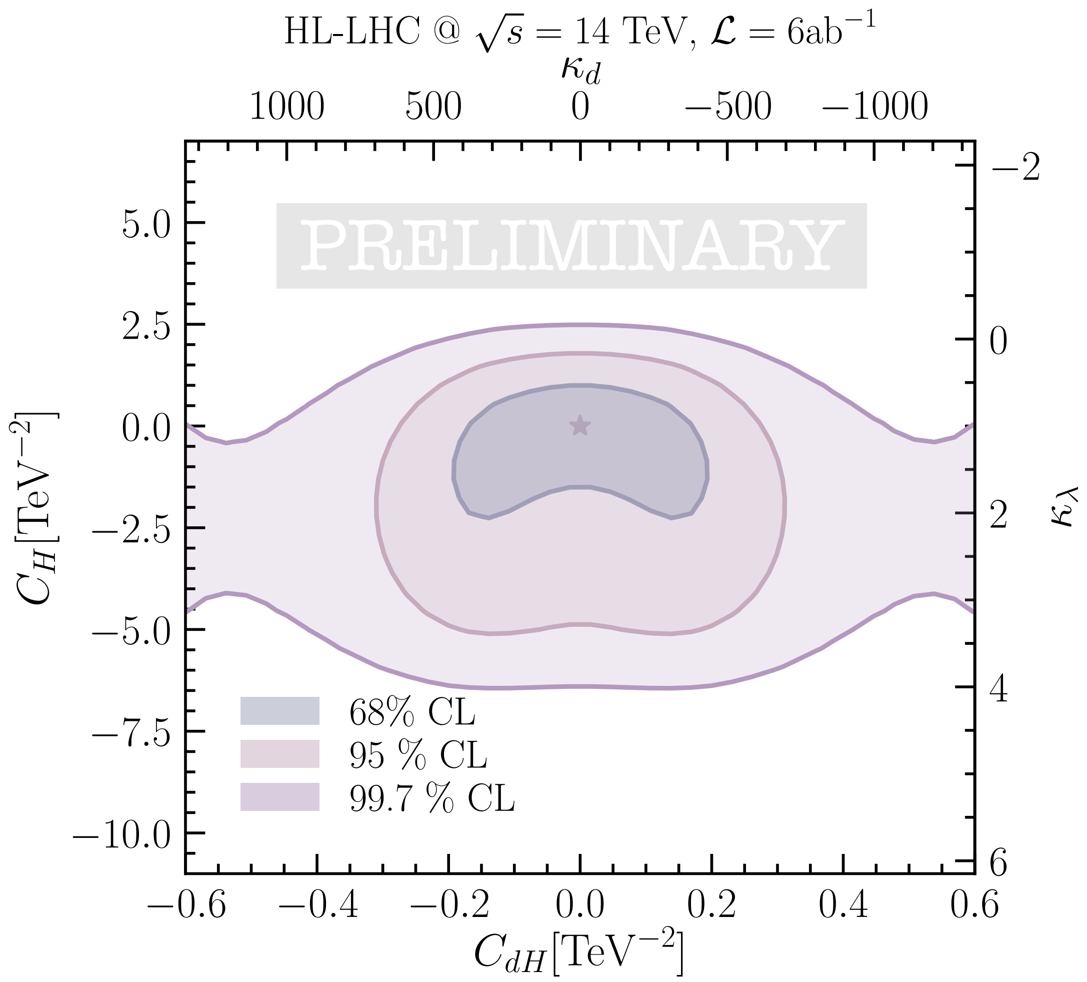
Statistical analysis

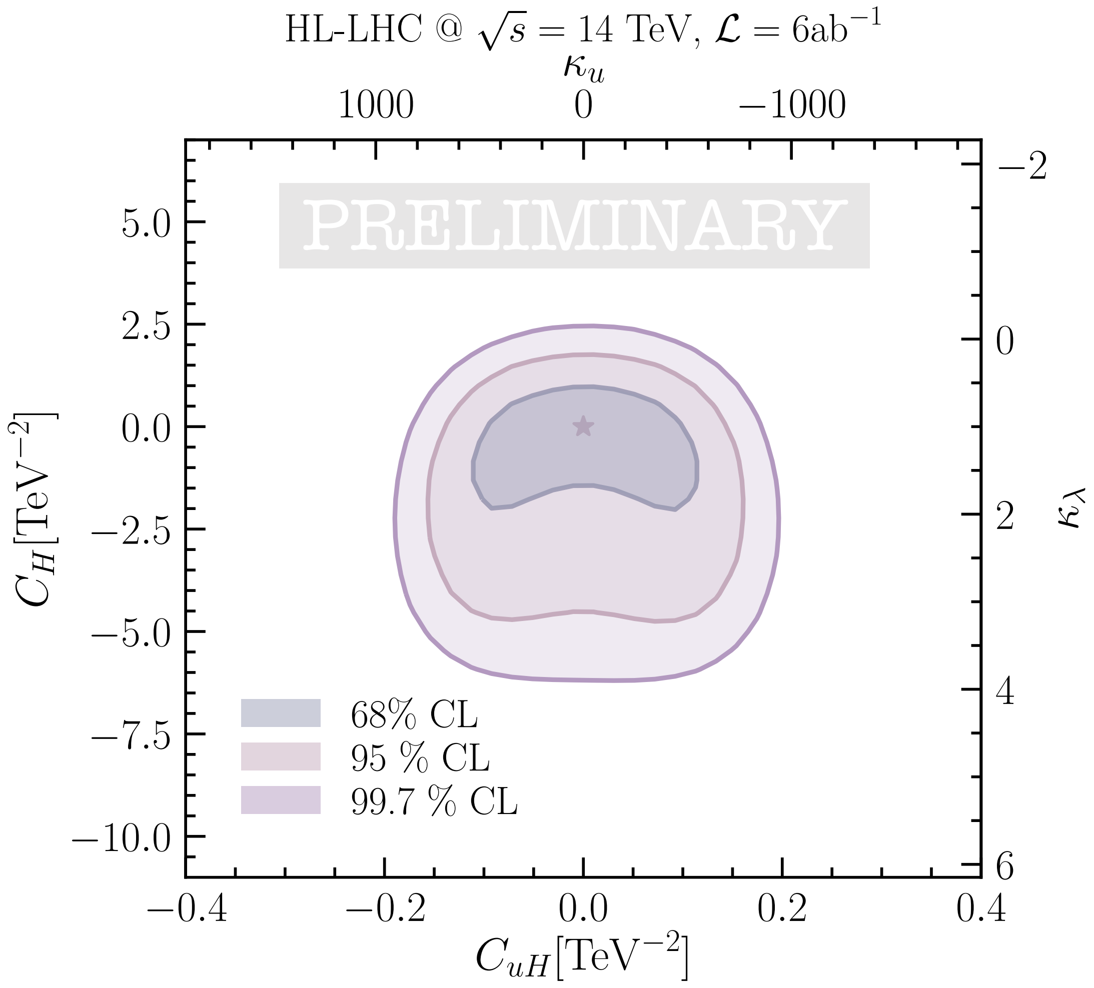


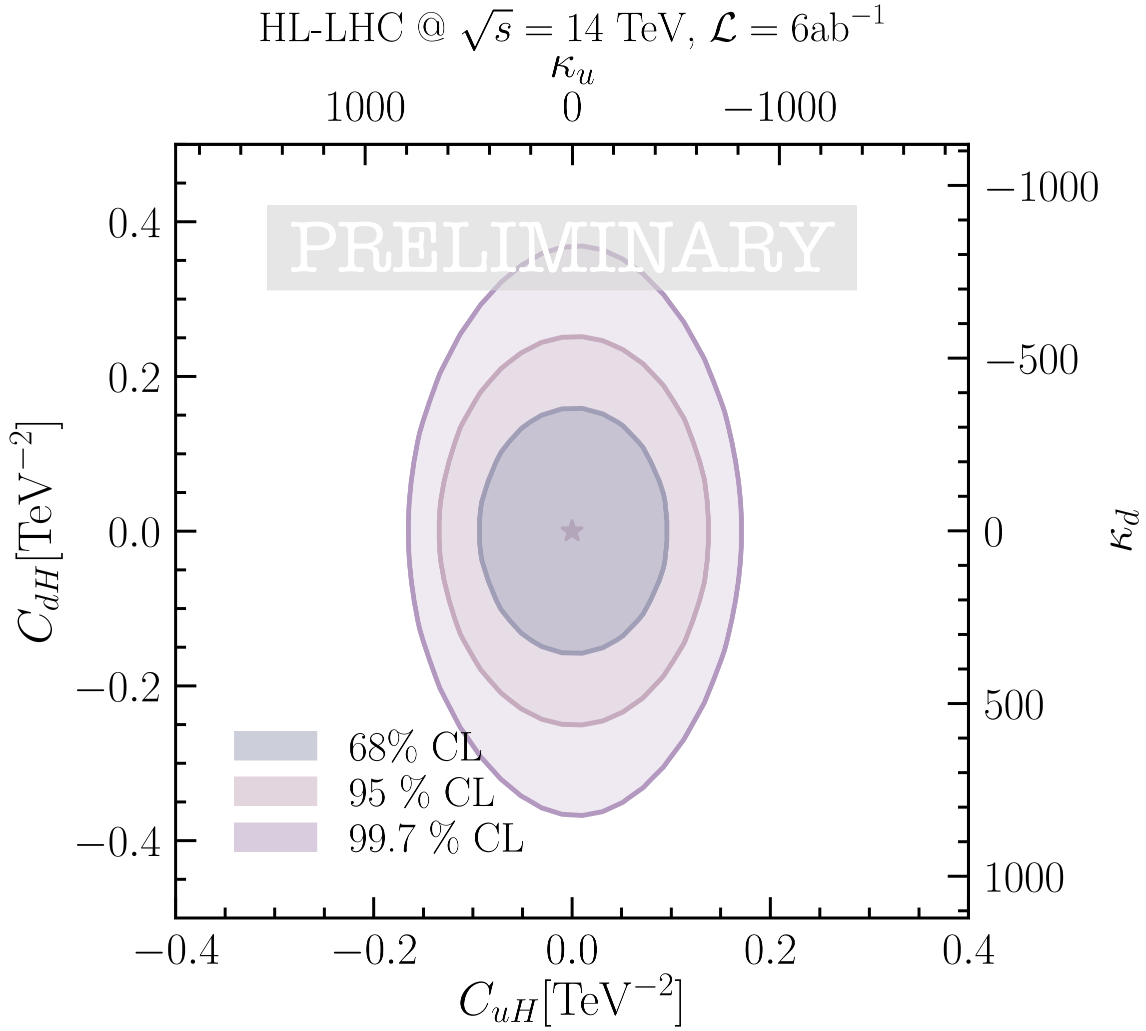
Build likelihoods

Yukawa's from Higgs² production

Alasfar, Gröber, Grojean, Paul, Qian, in progress







Summary

Determination of light Yukawa's is challenging.

Surprising that very different processes lead to bounds in the same ballpark at HL-LHC.
Still true at Future Colliders, in particular FCC-hh?

Simple flavour structures, like MFV, likely out of reach at HL-LHC.

Other flavour structures, like Spontaneous Flavour Violation or Aligned Flavour Violation from multi-Higgs models or special models with vector-like quarks, can be tested directly in Higgs physics.

Future direction: CPV Yukawa's…